Session 1608

The Evolution of an Introductory Biological Engineering Course: Design is the Endpoint!

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Abstract

Four the past four years, I have taught the sophomore level course, Agricultural Engineering 243 *Material and Energy Flows in Biological Systems* each spring semester. During the first offering, I used the lecture method to transmit information, and homework assignments and exams to reinforce skills and test comprehension. The greatest weakness of this technique seemed the lack of hands-on experience which I gave my students, and their subsequent lack of physical intuition. Enhancing their physical intuition drove the first curricular revision – using in-class demonstrations and simulations of key physical and biological processes. This technique did not work as well as expected, probably because it continued to rely on a source - sink model of learning, with myself as the fount of knowledge. Therefore, increasing student involvement and fostering student maturity drove the second revision, consisting of the inclusion of two team design experiences, and the addition of more student-led problem solving during class time. This second revision was very rewarding, achieving a >95% attendance rate over the semester, and strongly positive student evaluations. By making engineering design central to the class, student maturity and student interest were increased, and their educational needs better served, than in the traditional lecture format. At the time of this writing, the third revision of the course is underway. I am now distributing printed class notes to transmit technical information, and relying on problem sets, quizzes, a semester long design project, and student initiated discussions to reinforce the material. Again, the non-lecturing, design focus of the course appears to be achieving high student attendance and interest. These experiences have convinced me that incorporating engineering design into lower division engineering courses enhances student learning and can make the teaching of engineering more fun.

Introduction

Lower division engineering courses are the foundation of engineering education. Without a mastery of engineering fundamentals, students are poorly prepared to do engineering analyses, which is a critical part of engineering design. The breadth of agricultural and biosystems engineering makes selection of topics for an introductory biological engineering course difficult. Covering too broad a swath of subjects can turn a core-engineering course, which should impart mastery of critical engineering concept, into a survey course, which dabbles in an interesting array of subjects but imparts no mastery of any. It is therefore necessary for individual instructors to focus on sub-sections of biological engineering to provide their students with a core-engineering experience that enhances their understanding of biology, physics, chemistry and mathematics, in the context of engineering design. My experience with fourth-year engineering students has shown that the core concepts of mass and energy balances are frequently not mastered by this point, nor are certain mathematical, economic, and computer fundamentals. Thus, the focus of my introductory biological engineering course, AE 243 *Material and Energy Flows in Biological Systems* has been on these topics. However, the methods of presenting this material, as well as the mixture of technical content, have evolved over the past four years, and these changes are reported herein.

Students in our department can select from five de facto concentrations, as follow: agricultural engineering with soil and water emphasis, agricultural engineering with power-machinery emphasis, agricultural engineering with processing emphasis, biological engineering, and food engineering. Currently, all students except those concentrating in the power machinery area, are required to take AE 243. Those concentrating in biological engineering have significant biologically related courses in their program (Table 1), allowing AE 243 to focus on core engineering topics *in a biological context*, as opposed to being a biology course with some engineering content thrown in.

AE 243 was developed and taught (by the author) for the first time in the spring of 1994, and has been taught every spring semester since. The 3 semester-hour course meets three times a week for 50 minutes. The course grew out of the goals mentioned above, and out of a senior-level bioprocess engineering course taught at Cornell University (Walker, 1993). During my first year of graduate school I had taken this course; in subsequent years I guest lectured in the class and developed a case study for the class. In my final year of graduate school I taught the course, while my advisor was on sabbatical leave. AE 243's emphasis on energy balances and enzyme kinetics are manifestations of Dr. L. P. Walker's vision of biological engineering.

Course	**Catalog Descriptions (from the 1996-1997 University of Tennessee Undergraduate Catalog)**
General Biology I & II	Biology of cells; chemical basis of life; cell structure and function; energy metabolism; cell division; Mendelian and molecular genetics; kingdoms of monera, protista, and fungi; plant and animal anatomy, physiology, growth and reproduction; ecology; population genetics; behavior and evolution
General Chemistry I & II	A general course in theoretical and descriptive chemistry. Modern atomic theory; chemical bonding; stoichiometry; quantitative treatment of gas laws; quantitative aspects of solution chemistry; kinetics; chemical equilibria; thermochemistry; descriptive chemistry of non-metallic and metallic elements; electrochemistry; introduction to organic and biochemistry
General Microbiology	General properties of bacteria and viruses including physiology, metabolism, genetics, applied bacteriology, pathogenesis, and immunity
*Material and Energy Flows in Biological Systems** ***subject of this paper**	Introduction to mass and energy balances and enzyme and membrane function through the study of plants, animals and microorganisms. Topics include: terrestrial energy balances; enzymes and reaction rates, plant energy budgets, animal energy budgets and waste production; mathematical descriptions of microbial growth; and introductory chemical reactor theory.
Transport Processes in Biological Systems	Analysis of biothermal systems with emphasis on thermal energy and mass transfer. Thermodynamics, conduction and convection heat transfer, and mass transfer.
Processing Food and Biological Materials	Application of basic engineering sciences to processing and handling of biological materials: physical properties, thermal processing, drying evaporation, refrigeration and freezing, membrane processes and extraction.
Biophysical Chemistry I[1]	Physiochemical systems with applications to biological systems. Thermodynamics; chemical equilibrium; solution chemistry; transport; electrochemistry; kinetics; enzyme catalyzed reactions
Bioprocess System Design and Analysis	Design of processing, storage and handling systems for biological materials. Mass and energy balances, product and waste characterization, equipment specifications, economic analysis, safety and human factors.

Table 1. Biology related courses taken by Agricultural Engineering students with concentration in biological engineering.

[1] At the time of this writing, and at the author's suggestion, the department's curriculum committee is recommending that biological engineering students be given the option to take either this course or a traditional mechanical engineering thermodynamics course, due to the difficulty level of Biophysical Chemistry.

First Year's Experiences

Five students were enrolled in the spring 1994 offering of the course. The main topic areas planned for the course were as follow:

- The sun and energy balances, including coverage of radiant heat transfer, and of humanity's energy needs.
- Enzymes, mass balances and chemical reactions, including an overview of important biological molecules, a review of bonding (explained in terms of energy troughs), a discussion of protein structure and function, and coverage of introductory enzyme kinetics, using the Michaelis-Menten kinetic model.
- Plants, membranes, and energy balances, including conduction and convection heat transfer, the concept of chemical potential, membrane bound proteins and their role in nutrient uptake, photosynthesis, and respiration
- Microbes and reactors including classification of microorganisms, growth patterns of microbes in pure cultures, kinetics of substrate-limited microbial growth using the Monod equation, and comparisons between batch- and continuous flow-reactors

Grading was based on class participation and quizzes (10%), weekly homework sets (30%), a mid-term examination (25%), and a comprehensive final examination (35%).

This schedule was, in retrospect, hilariously ambitious. While it may have been possible to cover this material in the 15 weeks available, *covering material and teaching students are not synonymous*. The mid-term exam bore this out clearly; until that point the course had been moving according to plan. But the midterm results were dismal (57% average), and strongly indicative of a failure on my part to adequately explain the fundamentals of mass and energy balances. A two week period after the mid-term was spent carefully reviewing these fundamentals, and the course contents were reduced to allow slower, more considered coverage of the remaining material.

Student performance ranged from excellent to poor, with two students making A's, one making a D, and an average grade of 3.1/4.0. Student evaluations of the course were highly positive, though the survey instrument used was rather blunt, having only six questions, and not explicitly evaluating course content. The overall teaching effectiveness was rated as outstanding, as was the preparation and availability of the instructor.

When describing phenomena such as convection heat transfer, I had appealed to the students' physical intuition by asking them to do thought experiments. While this technique worked with some students, it seemed to fail completely with others. I was convinced that this reflected a lack of experience with physical systems, and that the most important thing to do for the upcoming year was to incorporate hands-on experiences into the course; the development and use of a series of in-class demonstrations and simulations was therefore the primary modification made to the course during the second offering.

Second Year's Experiences

Five students were enrolled in AE 243 in the spring 1995 offering of the course. The course content was similar to the first year, but I intended to include 13 in-class demonstrations of important course concepts (Raman and Wilkerson, 1994). Grading was on the same basis as the previous year.

Due to time and space limitations, only seven of the 13 demonstrations were developed and used during the class, while four others were partially prepared, but not used. Spending time on the demonstrations took far more time than I had anticipated, and did not seem to bring about the hoped for increase in physical intuition, or class participation. However, the slightly reduced technical content, combined with more realistic expectations on my part, did improve student performance on exams, and there was not a need to make a major mid-semester course shift.

Student performance in the second offering of AE 243 was moderate, with grades again ranging from D to A, but with an average of 2.9/4.0, representing a slight drop since the first offering. Course evaluations were by the same instrument as the first year, and the results were similar. However, the overall teaching effectiveness dropped from a 4.0/4.0, to a 3.75/4.0.

A Swift Kick Toward Design

Between the second and third year offerings of AE 243, I had the opportunity to co-teach a senior level design course with Dr. Ronald Yoder (see Raman and Yoder, 1997a & b for details). Our experiences during the first semester of this course profoundly influenced my goals for AE 243: Specifically, incorporating design, independent learning, and computer use were priorities because our senior engineering students were uncomfortable with all these activities. Therefore, in the spring of 1996, AE 243 was taught with a significant emphasis on design and team learning.

Third Year's Experiences

Six students were enrolled in AE 243 in the spring 1996 offering of the course. The course content was similar to the previous years, but most in-class demonstrations were dropped, and two team design projects were added. Grading was more heavily based on homework and design activities (now 40%, previously 30%), while the mid-term and final together counted for 50% of the total grade, rather than 60%. The class participation grade, as well as the design activities, were team graded, thereby making approximately 20% of the total grade team-based.

The first design problem was allotted two weeks to complete. The problem statements follows:

"A large home garden equipment company is interested in exploring the possibility of an electric lawn tractor. They envision a vehicle capable of mowing 3 acres on a single charge, with a weight no greater than 150% of their 10 hp gas model, and a cutting capacity similar to the 10 hp gas model. They also envision a solar panel option that will allow recharging of the mower in five days of moderate sunlight. They have hired your consulting firm to evaluate the feasibility of the power train for such a machine...."

In this case, each three person team was required to produce a professional quality feasibility report for the client, indicating cost estimates, design criteria, and a sensitivity analyses of power-train cost to battery type. Although this problem was essentially abiotic in nature, it was introduced at the very beginning of the course, when the concepts of energy, power and efficiency were covered. These concepts must be mastered before more complicated systems, such as bioreactors, are analyzed. Successful completion of the design problem required that students use energy and power calculations, along with manufacturer's catalogs, reasonable assumptions, visits to the local home and garden store, spreadsheets and word processors. Both teams made excellent reports, and all students seemed excited by the process.

The second design problem was meant to be biologically relevant, and was to include a build and test phase in the project. Coming up with a suitable problem was harder than I expected, due to time constraints, the desire to build and test the system, and the desire to let the possible solution space be broad. I settled for a rather unrealistic problem, as follows:

"Design a completely sealed microcosm (volume between 1 and 10 L, your choice) that can support 10 earthworms for a period of two weeks..."

The design statement clarified that the microcosm could exchange energy with its surroundings, but not matter, and that the earthworms and their progeny, if any, had to be alive at the end of the two week period. Sub-tasks for the design included determining system parameters that would need to be controlled, listing biological and non-biological factors (such as the transmissivity of the container walls, and the respiration rate of the earthworms) that would need to be considered in the design, coming up with multiple proposals, and building and testing the system. The class was again split into two three-person design teams for all but the build and test phase, which was done as one large group. As far as the worms were concerned, the project was a complete failure; the system was too moist, and mold proliferated in the chamber while the worms died. However, to the extent that students took responsibility for developing project timelines, looking up information in the libraries, engaging in brainstorming sessions, and generally being more interested in the lecture content of the course than ever before, the project was a success.

Student performance in the class reflected the success of the design approach; the grades ranged from C+ to A, but the average was a 3.58/4.0, significantly higher than in previous years. Also, as mentioned earlier, class attendance was nearly 100% over the entire semester, a marked increase over the previous year. Course evaluations now used a much more sensitive survey tool (22 questions vs. 6 in the previous cases), and several interesting points came out. Notably, students rated the course as a whole, amount learned and relevance at > 4.5/5.0. Reasonableness of assigned work garnered the low score of 4.0/5.0, which corresponds to very good. Although the survey instrument changed, I believe that the third year's class was far more positive about the course than were the previous classes. In their written comments, five of six students identified group work and/or the project as contributing greatly to their learning.

Due these experiences, I decided to invest wholeheartedly in the design approach. Furthermore, while short design experiences are undoubtedly useful, there is no substitute for semester (or multiple semester) design experiences that include building, testing and evaluation phases. These phases are used to re-introduce hands-on engineering practice, which was one of the original goals of the defunct lecture demonstrations. Therefore, during the current offering of AE 243, the class is engaging in a semester long design project to develop a small-scale biological waste treatment system.

Fourth (Current) Year's Experiences

There are currently 11 students enrolled in AE 243. This 100% increase over past classes reflects both a slow growth in our overall student numbers, and a number of seniors who are taking the class out of sequence, or as a technical elective.

Course content has been modified to further emphasize fundamentals, and to focus on microbial growth and wastewater treatment, while plant function and chemical kinetics have been de-emphasized. The increased attention to microbes reflects the design problem, which involves using microbes to clean a synthetic wastewater. The main topics of the course follow:

- Introduction to the engineering design process, including problem presentation, definition, synthesis, analysis, construction, testing and evaluation. Discussion of the importance of mathematics to engineering analysis.

- Energy conservation and transformation, including energy balances, qualities of electromagnetic radiation, radiation heat transfer, power balances, steady-state and non-steady-state cases.

- Important biological molecules, including a discussion of polar and non-polar molecules, the importance of polar interactions to protein structure, and characterization of organic carbon content through BOD.

- Microbes and reactors including classification of microorganisms, growth patterns of microbes in pure cultures, using yield to link microbial growth to substrate depletion, the kinetics of microbial growth, and mathematical modeling of microbial growth in substrate limited batch reactors.

- Heat and mass transfer, including conduction, convection, radiation, and evaporative modes of heat transfer, and diffusion and convective mass transfer. If time allows, we will also cover active transport in cells.

Delivery of technical material has also changed drastically. First of all, to further involve students in the technical material, I have given up lecturing, at least in the traditional sense. Each week I prepare a set of self-study course notes and problems, and hand them out to the class. During the following two classes, students can come to class and ask questions regarding those notes. I answer these questions (or occasionally other students do), and expand upon important concepts in the process. In addition, to accommodate the design, one class period per week is devoted to quiz taking (25 min.) and to a discussion of design issues (20 min.). This is also the day that homework assignments are collected, and that the following week's notes are distributed. In keeping with a departmental effort to enhance the computer skills of our students, all homework assignments must be done on word processors (written responses) or spreadsheets (calculations and graphs).

The design statement is as follows:

"10 L of wastewater is to be processed in a strictly biological waste treatment system (BWTS). In one week, the BWTS must remove 90% of the 5-day biochemical oxygen demand (BOD_5) and 90% of the total nitrogen. The pollutant concentrations of the waste are [BOD_5] = 20,000 mg/L (sugar and starch mixture), and 5 mM ammonium nitrate. There are no solids in the wastewater."

"Allowable inputs to the BWTS are seed organisms, distilled water, air and light..."

The required products include a working system, full documentation of the design, a poster to explain the system and describe its performance, and a presentation to the faculty. Students have the entire semester to work on the project, and are currently (8th week of 15) completing construction of the reactors and testing preliminary versions of their designs. The class is divided into three teams, and each team has decided on a different technique; one is using a sequential aerobic-anaerobic system for microbial carbon and nitrogen removal, one is using soil columns to treat the wastewater, and one is relying on an aerobic yeast culture for carbon removal followed by a hydroponic system for nutrient removal.

The lecture format appears to be working. The first three weeks were extremely uncomfortable for all of us; students didn't have many questions and appeared very unhappy with the "non-lecture" format. However, at the time of this writing, approximately eight weeks into the semester, students appear to be adapting well to the new course format. Given the small sample size, and lack of a good control group, it is hard to determine whether similar results could be achieved with the traditional lecture format. However, when data is lacking, one must operate on values; and I am convinced that teaching students to read notes and work problems by themselves *prior to coming to class* is very important, especially in light of a rapidly changing workplace and need for life-long learning on the part of engineering professionals. Students have done an excellent job of spreadsheet use, where they have all become facile at clearly documenting calculations and unit conversions.

The design has had its problems. The largest is that students don't have the requisite technical expertise at the beginning of the semester to begin the design, yet need to start working to allow sufficient time to build and test a system. They have therefore done far less analyses than I would have liked, prior to building their systems. However, this is part of the price of incorporating semester-long design experiences into most engineering curricula: we seldom have the luxury of working with students who have all the technical background necessary to begin a design. The positive aspect of this situation is that when you do start covering technical material that's relevant to the design, the students are completely engrossed by it; *you don't need to convince them of its relevance*.

Student grades at mid-term average 89%. Comments received during an anonymous survey of students at the time of this writing indicated that the design portion of the course is critical to their learning, and that most students are satisfied with the non-lecture format. The main complaint was about some of the mathematics covered in class; students felt that it was too concentrated, and recommended spreading it out over several weeks. I will attempt to do this in next year's offering.

Conclusions

As Marshall Lih humorously suggested in his commentary entitled *The Parable of Baseball Engineering* (Lih, 1996), engineering schools need to do far more than teach engineering science, mathematics, and other subjects as independent, unrelated topics. Rather, the practice of engineering is fundamentally linked to solving problems, which inevitably involves teamwork, time-management, engineering analyses supported by a genuine understanding of the biology, chemistry and physics of the problem under study, and the ability to communicate effectively with other people. In my experience with AE 243, bringing such issues to the fore through a focus on design problems greatly enhances student performance and interest. Thus, not only is this a way to make our courses more relevant, it is a way to make our students more interested, and to have more fun in the classroom.

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